The Neanderthal problem and the prospects for direct dating of Neanderthal remains

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Synopsis

There is at present no satisfactory absolute chronological framework for the Upper Pleistocene interface between Neanderthal and anatomically modern hominids. Existing relative and radiocarbon dating methods provide only a secondary means of correlation, and many important fossil hominid specimens, for historical reasons, cannot even be assigned a satisfactory relative date. The development of a new method of radiocarbon dating by means of particle accelerators, which only requires small samples of organic material, offers the possibility of dating the fossil remains of Neanderthal man directly for the first time. This should allow the known fossil record, and also future discoveries, to be placed in a precise chronological and evolutionary framework.

Introduction

A remarkable fossil human cranium was discovered during work at the Forbes' Quarry, Gibraltar, in 1848 (Fig. 1; Oakley, Campbell & Molleson 1971). Its unusual appearance immediately attracted attention but it was not until 1865 that a scientific analysis of the specimen was published (Busk 1865). Thus by an accident of history the names 'Gibraltar man' and '*Homo calpicus*' (proposed by Falconer in a letter to Busk in 1864, after an ancient name for Gibraltar, Calpé) did not achieve scientific currency, for one year earlier the anatomist William King had designated a similar but more fragmentary fossil cranium from Germany as the type of the first recognizable archaic species of man, *Homo neanderthalensis* (King 1864, Oakley 1964, Oakley, Campbell & Molleson 1971). The specimen discussed by King had been discovered during quarrying operations which had penetrated a series of caves in the Neander Valley, near Düsseldorf, in 1856.

Much of the argument about these human fossils centred around their unusual cranial morphology, but although it was assumed by most workers that they represented ancient inhabitants of Europe, these historically important specimens could not be dated accurately since neither fossil was excavated systematically nor had associated faunal or archaeological remains. It was only after 1886, with the discovery at Spy, Belgium, of comparable remains unequivocally associated with a mammalian fauna which included the cold-adapted mammals *Coelodonta, Mammuthus* and *Rangifer*, that it could be inferred that the Forbes' Quarry and Neanderthal specimens probably dated from the same ancient glacial period. Even at the present time, no more accurate assessment of the relative or absolute age of these important fossils can be made than 'inferred Early Würm' (Oakley, Campbell & Molleson 1971).

A second and equally critical problem concerning the dating of Neanderthal hominids was their relationship to fossils of early anatomically modern (a.m.) *Homo sapiens* (used in the sense of Howells 1974). It had been realized for some time before 1886 that more modern-looking human fossils were also associated with faunas suggesting periglacial conditions, as

Bull. Br. Mus. nat. Hist. (Geol.) **35** (3): 225–241

Issued 29 October 1981

Fig. 1 Right lateral view of the cranium discovered in Forbes' Quarry, Gibraltar, in 1848. BM(NH) reg. no. FC 278.7. × $\frac{1}{2}$.

at French sites such as Cro-Magnon, Bruniquel and La Madeleine (Oakley, Campbell & Molleson 1971). Did, therefore, the populations of Neanderthal and modern man co-exist, or did one group antedate the other? The answer to this problem came through more careful excavation of a number of cave sites, and study of the stratigraphical relationships of archaeological remains. It was recognized that many of the fossil remains of a.m. *H. sapiens* found in French caves were associated with stone tool industries based on blades (long, narrow flakes of flint or other raw material, struck from prepared cores) and that much use was made of other raw materials such as bone, ivory and antler. Sometimes, stratified below these blade-tool industries, were industries of a different character without the predominance of blade-tools, and with little use of bone, ivory and antler. Such industries were found directly associated with Neanderthal skeletons at sites such as Spy, La Chapelle, La Quina, La Ferrassie and Le Moustier, and they were given the collective name Mousterian (also known as Middle Palaeolithic). This was to differentiate them from those of the succeeding Upper Palaeolithic industries, such as the Aurignacian, Perigordian, Solutrean and Magdalenian (Oakley 1964).

Thus by archaeological inference it was established that the Neanderthals probably antedated a.m. *H. sapiens* populations within what was eventually recognized as the last major glacial advance of the Pleistocene epoch. However, the extent of the time-gap between the two populations could only be guessed at before the advent of absolute dating methods, and the simple and abrupt archaeological division between the Mousterian and Upper Palaeolithic has become increasingly blurred following further research in Europe and south-west Asia (Bordes 1968, Lumley 1976).

The evolutionary significance of Neanderthal Man

Because of their use of caves as habitation sites and their introduction of burial practices, the Neanderthals are much better represented as fossils than any earlier Pleistocene hominids. The sample of Neanderthal fossils from Europe and Asia has grown markedly this century, and now represents several hundred individuals ranging in age from foetal to aged. While the majority of the specimens are fragmentary, several fairly complete skeletons have been excavated, and at some sites such as Krapina (Yugoslavia) and Shanidar (Iraq) many different individuals are represented (Smith 1976*b*, Trinkaus 1977, Wolpoff 1979). This has added to the importance of the Neanderthal sample since, in addition to detailed anatomical analysis, it is possible to attempt to study the actual biology of Neanderthal groups, investigating their health and population structure (e.g. level of sexual dimorphism, ages at death etc.) (Trinkaus & Howells 1979, Wolpoff 1979, 1980*a*, *b*, Trinkaus 1980, 1981, Smith 1980). But one of the difficulties with this kind of study, whether using material from one or from several sites, has been the problem of the time-span covered by the sample under investigation. Accurate dating of the Neanderthal specimens would allow much greater refinement in the study of their variability through time and space.

As already discussed, the stratigraphical position of Upper Palaeolithic industries, inferred to be the product of a.m. *H. sapiens*, above Mousterian industries, inferred to be the product of Neanderthal populations, demonstrated that Neanderthals existed in Europe at an earlier date than a.m. *H. sapiens*. From time to time the even earlier existence of a.m. *H. sapiens*, or a nearly-modern ancestral form, was claimed from sites such as Swanscombe (England) and Fontéchevade (France). If confirmed, this evidence would have relegated the Neanderthals to a side-branch of human evolution. However, the evidence for a modern morphology in these fossils is now regarded by most palaeoanthropologists as unconvincing (Stringer 1974, 1978, Wolpoff 1980*a*, *b*), so in looking for the ancestors of a.m. *H. sapiens* in Europe and south-west Asia, need we look any further than their immediate predecessors, the Neanderthals?

Two extremes of interpretation still dominate the arguments about the relationship between Neanderthal and a.m. *H. sapiens* populations, although there are also many intermediate viewpoints. One extreme view is that there must have been an evolving continuum in human populations of the Upper Pleistocene, with the Neanderthals gradually evolving into more modern-looking populations. Thus dating the Neanderthals accurately would be of critical importance since, in the simplest terms, the earliest Neanderthals would be less like modern humans, while the late Neanderthals would almost imperceptibly blend into the earliest a.m. *H. sapiens* populations (Brace 1964, Brose & Wolpoff 1971, Frayer 1978, Wolpoff 1981).

At the other extreme, the population-replacement model postulates that the Neanderthals were a specialized group of hominids with their own distinctive characteristics, and that they were replaced quite suddenly during the middle part of the last glaciation in Europe by more modern-looking populations. To test this view would also require accurate dating of the Neanderthal specimens, since they would be expected to show little evolutionary change in the direction of modern humans through time, and their replacement would have been abrupt, with a clear Neanderthal morphology existing right up to the sudden morphological discontinuity in the fossil record, represented by the appearance of completely distinct a.m. *H. sapiens* (Howells 1974, 1975, Stringer 1974, 1978). Furthermore, the sudden appearance of a.m. *H. sapiens* populations in western Europe would presuppose their existence at an earlier date in some other area; it would be expected that accurate dating would demonstrate the occurrence of early a.m. *H. sapiens* fossils in some areas contemporaneous with, or even earlier than, the Neanderthal fossils of western Europe (Stringer, Kruszynski & Jacobi 1981).

A less extreme view postulates a longer co-existence of the two forms of hominids in Eurasia, with some degree of gene flow and cultural diffusion between them, but in this case there must have been some adaptive or behavioural factors which maintained the discreteness of the two populations through time. Another model suggests that a.m. *H. sapiens* evolved out of some geographically restricted part of the Neanderthal range, perhaps in eastern Europe or south-west Asia, where it has been suggested that the Neanderthal populations of the Upper Pleistocene were less extreme in their characteristics (McCown & Keith 1939, Howell 1957). A comparable model is that of 'punctuated equilibria' (Gould & Eldredge 1977), whereby the change from a relatively stable Neanderthal morphology to a relatively stable a.m. *H. sapiens* morphology could have been achieved through a short burst of evolutionary change accomplished in a peripheral part of the Neanderthal population range. The evolutionary changes then spread rapidly from that area replacing the previous morphology. All of these models can only be tested adequately against the fossil and archaeological evidence if that evidence is well dated.

Archaeological evidence

The term 'Mousterian', as mentioned already, is the collective name first used in the last century for the stone tool industries which immediately preceded those of the Upper Palaeolithic in Europe, and which were attributed to Neanderthal populations. However, more recent excavations and study have shown that several well-defined and distinct assemblages can be recognized within the broad category of 'Mousterian'. This term in fact represents a stage of cultural evolution where flakes, made by the Levallois technique in some cases, were retouched to produce, in varying proportions, side-scrapers, notches and denticulates. Handaxes, Mousterian or Levallois points, and some 'Upper Palaeolithic' types of tools may also occur. The distinct variants of the Mousterian recognized in western Europe are the Mousterian of Acheulian Tradition, the Quina-Ferrassie, Denticulate and Typical Mousterian (Bordes 1968). Comparable kinds of industries have also been described elsewhere in Europe, in western and south-western Asia, and in north Africa (Bordes 1968). Although doubts have been raised about the significance of Mousterian assemblage variability (Binford 1973), it is possible that each of the Mousterian varieties had a long and predominantly independent evolution during the early part of the last glaciation and that they may have been the products of distinct co-existing ethnic groups. Relative chronologies have been proposed for some of the main archaeological sites and Mousterian varieties, and some of the most important Neanderthal fossils have been assigned a relative date by means of such correlations (Bordes 1973, Lumley 1976).

However, the simple equations 'Mousterian = Neanderthal' and 'Upper Palaeolithic = a.m. *H. sapiens*', which represent the underlying assumptions behind many evolutionary frameworks formulated in the absence of absolute dates, have given way in the last few years under the weight of new discoveries. Models closely linking technological change and human evolution, which also place much reliance on such a framework, must now be modified. Three sites have been critically important in emphasizing that the anatomy of the manufacturers of Mousterian or Upper Palaeolithic industries could *not* be assumed to be known in the absence of clear osteological evidence. Skhūl and Qafzeh, in Israel, are two sites where a Mousterian technology is clearly associated with fossil hominids representing a.m. *H. sapiens*, albeit an early and robust form (Howells 1970, Stringer 1974, 1978, Vandermeersch 1977). Excavations at the third site, Saint-Césaire, in France, have recently revealed an apparent Neanderthal burial in an early Upper Palaeolithic archaeological context – that of the Châtelperronian (Lévêque & Vandermeersch 1980). Interestingly, this last find has demonstrated for the first time that the continuity between the Mousterian of Acheulian Tradition and the Châtelperronian industries, which had been suggested by archaeologists, was apparently paralleled by a physical continuity in Neanderthal populations from Würm II–Würm III (French usage) (ApSimon 1980).

Thus it would appear that both Neanderthal and anatomically modern forms spanned the transition or gap between Mousterian and Upper Palaeolithic technologies, and this revelation will have tremendous repercussions on archaeological and anthropological thought. Certainly it appears an inescapable conclusion that in Eurasia a.m. *H. sapiens* evolved from an ancestor associated with the Mousterian level of culture. However, it is no longer safe to assume that therefore the antecedent was necessarily a Neanderthal *sensu stricto*. Moreover the likelihood that Neanderthal and a.m. *H. sapiens* populations co-existed in adjacent areas, if not the same areas, seems greatly increased by recent discoveries (Stringer *et al.* 1981). The Saint-Césaire evidence, if taken at face value, could also imply a survival of Neanderthal populations into Würm III (French usage), with the further implication that these populations could have contributed to the ancestry of a.m. *H. sapiens* populations of the late Pleistocene.

A further complication is the apparently sudden arrival in western Europe of the Upper Palaeolithic Aurignacian industry at about the same time as the Châtelperronian industry had completed its hypothesized evolution from the Mousterian of Acheulian Tradition. There are no convincing local archaeological antecedents for the Aurignacian in western Europe and it is tempting to correlate the spread of Aurignacian industries from eastern to western Europe with a movement of a.m. *H. sapiens* populations, or genes, in the same direction. But as many previous assumptions about the relationships of industries to hominids are demonstrably incorrect, such a model needs stronger corroborative evidence than is available at present. This is particularly so as there is no convincing ancestral industry for the Aurignacian anywhere else either, although it can possibly be traced back to eastern Europe more than 40,000 radiocarbon years before present (bp) (Kozłowski 1979). Accurate absolute dating would certainly clarify the relationships of European Upper Pleistocene hominids and industries.

South-west Asian evidence

For some time, south-west Asia has assumed particular significance in discussions about the origin of a.m. *H. sapiens*. It has been suggested as the source of Upper Palaeolithic industries (McBurney 1977) and of early European a.m. *H. sapiens* populations (Howell 1957, Stringer 1974, 1978, Vandermeersch 1977). The main fossil hominid finds from this area are associated with Levalloiso-Mousterian industries, with the exceptions of the Zuttiyeh specimen, which may be associated with the earlier Acheulian of Yabrudian facies (Gisis & Bar Yosef 1974, Schwarcz 1980), and a few Upper Palaeolithic specimens. The Zuttiyeh fossil may be a local equivalent of the 'early Neanderthals' of Europe, and may be metrically distinct from later Neanderthal fossils (Stringer 1978).

However, the main sample of Neanderthal finds from south-west Asia (those from Shanidar, Tabūn and Amud) shares a number of characters with its European counterpart. In some respects it is distinctive and more like a.m. *H. sapiens*, but in other characters it is as different from a.m. *H. sapiens* as the most extreme of the European Neanderthal specimens. The second relatively large sample of Pleistocene hominids from this area is also associated with Levalloiso-Mousterian industries, but has been recognized as representing a.m. *H. sapiens* (fossils from Skhūl, Qafzeh and perhaps Ksâr 'Akil) (Brothwell 1961, Howells 1970, 1974, 1975, Stringer 1974, 1978, Vandermeersch 1977, Trinkaus & Howells 1979, Stringer & Trinkaus 1981). The problem of relating these two hominid samples to each other taxonomically and chronologically has not been resolved, but the issues involved parallel those discussed for the European area. One difference from the European situation is that the samples from the sites of the Shanidar, Skhūl and Qafzeh are large and relatively well stratified. Furthermore the Neanderthal/a.m. *H. sapiens* interface appears to occur against a Mousterian technological background, and is likely to be earlier than the European interface which occurs against a terminal Mousterian/early Upper Palaeolithic background. The exact time relationships involved are uncertain, although it is at least possible that some of the early a.m. *H. sapiens* specimens are broadly contemporary with parts of the Neanderthal sample (Farrand 1979).

The implications of the south-west Asian evidence for the European Upper Pleistocene succession are important. Firstly, it would appear that a.m. *H. sapiens* in Eurasia evolved from a Mousterian technological background, although the evidence from Skhūl and Qafzeh implies that this is not at all the same thing as saying that this evolution was necessarily from a Neanderthal ancestor. Secondly, if dating evidence can confirm the apparent earlier appearance of a.m. *H. sapiens* in south-west Asia, this would provide a possible genetic source for the appearance of comparable populations in Europe, or evidence that an even older parent population for both groups existed somewhere. Finally, with more reliable dating evidence, the relatively large samples of stratified hominid material from sites such as Shanidar and Qafzeh may allow a more detailed examination of evolutionary trends in these samples than is at present possible in Europe. Moreover the evolutionary framework to be inferred may be applicable to the European fossil hominid samples. Thus the south-west Asian sample is a particularly significant one for any interpretation of the place of Neanderthal man in human evolution, and a reliable chronological framework for it is vital.

Dating

Relative dating

Chemical analysis (and more recently, activation analysis) of nitrogen, fluorine and phosphorus in fossil skeletal remains, and radiometric assay of uranium, are well established relative dating procedures. These methods have been intensively applied to the relative dating of fossil hominids over the last thirty years by K. P. Oakley and he has recently comprehensively reviewed the results obtained for Pleistocene and early post-Pleistocene hominid remains from Europe (Oakley 1980). Remains of Neanderthal and related hominids from sites in Europe, north Africa and south-west Asia are among those that have been analysed in this way and the results compared where possible with analyses of stratified faunal remains from the same sites (Oakley *et al.* 1971, 1975, 1977). It is of historical interest to note the early application of fluorine analysis to human bone from Krapina, Yugoslavia by the discoverer of the site, K. D. Gorjanović-Kramberger (1901). But while these methods of element analysis can often help to resolve the age relationships of a particular group of fossil skeletal remains from a given site, the results cannot provide an exact time scale or permit fossils from different localities to be placed in a temporal sequence, nor indeed have any such claims been made for these methods.

Before the advent of absolute methods of dating, the only other way of estimating the relative ages of fossil human remains was through correlation of the respective deposits in which they were found, on the basis of the available geological, faunal and associated archaeological evidence (A4 dating, Oakley *et al.* 1971). This was attempted by Zeuner (1940) for some of the principal Neanderthal remains known at the time. With the advances in detailed knowledge of the history of the last glaciation that have taken place since then (many of the foundations for which were laid by Zeuner), the environmental and archaeological background, though not able to provide an absolute time scale, assumes if anything even greater importance in the interpretative study of the fossil remains (Lumley 1976, Farrand 1979).

Absolute methods of dating

A number of methods of absolute dating appropriate to the expected time scale of the fossil hominids of the later Pleistocene may be mentioned. These include the thermoluminescence (Göksu *et al.* 1974, Wintle 1980), electron spin resonance (Ikeya 1978), uranium series (Schwarcz 1980), potassium-argon (Bishop & Miller 1972), amino-acid (Masters, in press) and radiocarbon methods. Some of these, for example thermoluminescence dating of burnt, humanly worked flint and electron spin resonance dating of bone, are not yet fully workable methods. A much more important consideration, however, is whether a method can be applied directly to the fossil remains in question (A1 dating in the terminology of Oakley

1964), rather than indirectly to some other, stratigraphically related, material. Only two of the methods mentioned above (amino-acid and radiocarbon dating) currently satisfy the former requirement and of these only the radiocarbon method has been at all well tested at present.

Approximately 70 radiocarbon dates have been published for sites in Europe (mainly France), north Africa and south-west Asia, that have yielded Mousterian (or Levalloiso-Mousterian) industries, some of which may be the handiwork of Neanderthal man (information based on a computer search of the contents of *Radiocarbon* volumes **1–16** (1959–74) stored on magnetic tape, and visual search of *Radiocarbon* **17–21** (1975–79)). This is a small number in comparison with the total of 50 000 or so radiocarbon dates now published (of which rather less than half are archaeological dates), but must reflect to some extent the paucity of associated organic material suitable for dating surviving on early sites and the relative rarity of the sites themselves. About half of these dates are based on bone (collagen or burnt bone) from the remains of hunted animals and half on charcoal; by far the greatest number has been contributed by the Groningen laboratory, mostly prior to 1970. About 45 of the dates are finite and lie in the range 30 000–55 000 bp, most lying towards the younger part of this age range (30 000–45 000 bp); the remainder are cited as 'greater than' 30 000 bp, four being $>$45 000 bp. Probably even those published as finite dates with limits of error should be considered as minimum ages, because of the relatively greater effect that small amounts of younger contaminants, which it is very difficult to remove completely, can have on the apparent age of very old samples.

In all, 40 dates have been obtained, as summarized in Table 1, that relate to sites in Europe, north Africa, western and south-western Asia, at which the remains of Neanderthal and related fossil hominids have been found. Some of these dates merely provide a chronological basis for the stratigraphical sequence or a part of the sequence at a given site, not always that where the hominid remains were found. From these the dates of particular remains have been inferred, in some instances on very tenuous grounds, for example at Saccopastore, Italy. In other instances the primary objective has been to provide a date for the hominid remains and the association of the sample dated with the fossil remains is somewhat closer. Many of the remains that have been dated are, however, extremely sparse, some comprising only single teeth, and with certain exceptions (Shanidar, Iraq; Amud and Tabūn, Israel; Krapina, Yugoslavia; La Quina and Regourdou, France; Gibraltar) do not include some of the most complete fossils, nor those that are most significant from the evolutionary point of view. For many important fossils, for example the twenty or so individuals, some represented by fairly complete skeletons, from Qafzeh and Skhūl, Israel, absolute dates are lacking altogether and clearly many more dates are needed even for those remains for which some idea of the dating framework already exists. Minimum dates (that is, those given as greater than some lower limit of radiocarbon age, of which five are listed in Table 1) are inevitably of limited value. Clearly also, some of the dates listed in Table 1 (for example, the series for Amud and the date for the mandible from Bañolas, Spain) are too recent to be reconcilable with any credible model for the probable time scale of Neanderthal man's existence. Some others again, such as that for the temporal bone from Darra-I-Kur, Afghanistan, though perhaps falling closer to the age range that might reasonably be expected for the fossil remains, have been published with definite reservations as to their dependability (Krueger, in Dupree 1972). Most importantly of all, none of the dates at present available is an A1 date based directly on the fossil skeletal remains, that is on bone from an individual hominid, and it is in this important respect that there are now real prospects of a major advance.

Towards a direct and extended chronology

All the dates discussed above were obtained by the conventional gas-counting method for the measurement of low levels of radiocarbon, that is by detection of the radioactive beta-decay of atoms of ^{14}C. This is the basis also of the alternative conventional method of radiocarbon

Table 1 Neanderthal and related fossil hominid remains indirectly dated by radiocarbon. Sites have been arbitrarily listed by country from east to west and only finds from dated sites, or those for which correlations with other dated sites have been attempted, are included, together with the relevant radiocarbon dates. Following Oakley *et al.* (1971) the designations A2 and A3 in the date column denote the degree of association between the sample dated and the hominid remains. With the possible exceptions of dates obtained for remains from Bacho Kiro, Bulgaria (claimed early a.m. *H. sapiens* associated with an 'Aurignacoid' industry) and Vindija, Yugoslavia, for which full information was lacking, the list is believed to be complete. The information tabulated here was taken principally from *Radiocarbon*, New Haven, (*R*), vols **1–21** (1959–79) and from the (Oakley *et al.*) *Catalogue of Fossil Hominids* (*CFH*), parts **1–3** (1967–75; part **2** 2nd ed., 1977), as cited in the right-hand column of the table.

Site	Location	Date of discovery	Hominid remains	Radiocarbon date bp ($t_{\frac{1}{2}} = 5570$ yr)	Material dated and association	Lab. no.	Remarks	References
Darra-I-Kur, Afghanistan	36°44′N 69°59′E	1966	temporal bone	$30\,300^{+1900}_{-1200}$ (A2)	charcoal and soil organic matter	Gx–1122	sample associated with Middle Palaeolithic flakes and cores Mousterain	Dupree (1972): 3–84 (not published in *Radiocarbon*)
Shanidar, Iraq	36°50′N 44°13′E	1953, 1957–60	remains of at least 9 individuals represented by partial skeletons (Layer D; Shanidar 1–9)	50 600 ± 3000 46 900 ± 1500 (A2/3)	charcoal from hearth in top of Layer D	GrN–1495 GrN–2527	dates Shanidar 1 and by inference from stratigraphy, Shanidar 3 and 5; date of *c.* 60 000 bp inferred on this basis for Shanidar 2, 4, 6, 8 and 9; Shanidar 7 (infant) is stratigraphically older Mousterian	*R* **5** (1963): 173 *CHF* **3** (1975): 122 Trinkaus (1977): 9–33
Ksâr 'Akil, Lebanon	33°55′N 35°37′E	1947	fragmentary maxilla (Complex 3; Ksâr 'Akil 2)	43 750 ± 1500 (A3)	charred bone from layer 1 m below maxilla	GrN–2579	Mousterian/Upper Palaeolithic	*R* **5** (1963): 174 *CFH* **3** (1975): 164
Ras el-Kelb, Lebanon	33°56′N 35°36′E	1959	adult premolar (Ras el-Kelb 1)	> 52 000 (A2/3)	charred bone	GrN–2556	date for sample from correlated layer Levalloiso-Mousterian	*R* **6** (1964): 349 *CFH* **3** (1975): 165
Amud, Israel	32°52′N 35°30′E	1961, 1964	remains of 5 individuals, including cranium, mandible and most of skeleton (Amud 1) (Layer B;	10 600 ± 400 10 500 ± 140 9010 ± 160 11 500 ± 250 7340 ± 150 14 700 ± 310 15 700 ± 370 18 300 ± 400 11 700 ± 200	collagen and carbonate fractions of animal bone from Layer B1–B4	TK–12 TK–33a N–763 N–764 N–765 N–766 N–767 N–768 N–785	contamination suspected; fission track dating of bone from Layer B1–4: 28 000 ± 35% BP "Transitional" or mixed Levalloiso-Mousterian/Upper Palaeolithic	*R* **11** (1969): 511 *R* **11** (1969): 512 *R* **19** (1977): 81–83 *CFH* **3** (1975): 126

			Amud 1–5)	10 700 ± 190 13 100 ± 230 14 400 ± 350 (A2)		N–786 N–852 N–854		
Mugharet et-Tabūn, Israel	32°40′N 35°05′E	1929–34	fragmentary remains, mainly teeth, of 6 individuals (Layer B; Tabūn B1–BC6); fragmentary cranium, mandible and partial skeleton of adult female, remains from at least 4 other individuals (Layer C; Tabūn C1–C7)	39 700 ± 800 (A2)	charcoal from Layer B	GrN–2534	Levalloiso-Mousterian	*R* **5** (1963): 172 *CFH* **3** (1975): 144, 146 Farrand (1979): 376–377
				40 900 ± 1000 (A2)	charcoal from Layer C	GrN–2729		
				51 000 $^{+4800}_{-3000}$ (A2)	Layer C	GrN–7409		
Geulah (Cave A), Mt Carmel, Israel	32°40′N 35°05′E	1962	fragmentary ulna and 2 fragmentary tibiae (Layer B2; Geulah 1)	42 000 ± 1700 (A2)	bone ash from Layer B2	GrN–4121	Levalloisian	*R* **9** (1967): 119 *CFH* **3** (1975): 134
Mugharet el-Kebarah, Israel	32°33′N 34°57′E	1964, 1965	fragmentary remains of 2 infants	>30 000 (A3)	charcoal from upper Levalloiso-Mousterian level	L–336d	dated samples not directly associated with hominid remains Mousterian	*Science, N.Y.* **126** (1957): 1324 *R* **5** (1963): 174 *CFH* **3** (1975): 137, 140
				35 300 ± 500 41 000 ± 1000 (A3)	charcoal from underlying Layer F	GrN–2551 GrN–2561		
Haua Fteah, Libya	32°50′N 22°10′E	1952, 1955	2 fragmentary mandibles (Layer 33; Haua Fteah 1 and 2)	47 000 $^{+3200}_{-2300}$ (A2)	charred bone from Layer 33	GrN–2023	Levalloiso-Mousterian	*R* **5** (1963): 171 *CFH* **1** (1977, 2nd ed.): 68
Velika Pećina, Yugoslavia	46°17′N 16°02′E	1961	frontal bone (Layer j; Velika Pećina 1)	33 850 ± 520 (A3)	charcoal from top of Layer i	GrN–4979	not Neanderthal proto-Aurignacian	*R* **14** (1972): 60 *CFH* **2** (1971): 342
Veternica, Yugoslavia	45°51′N 15°53′E	1955	calotte (Veternica 1)	>43 200 (A2/3)	charcoal from immediately underlying layer	GrN–4984	not Neanderthal–intrusive to Mousterian?	*R* **14** (1972): 61 *CFH* **2** (1971): 342

Table 1—*cont.*

Site	Location	Date of discovery	Hominid remains	Radiocarbon date bp ($t_{\frac{1}{2}} = 5570$ yr)	Material dated and association	Lab no.	Remarks	References
Krapina, Yugoslavia	46°10′N 15°52′E	1899	fragmentary remains of perhaps more than 70 individuals, the majority immature	30 700 ± 750 (A2 ?)	charred bone from unrecorded level	GrN–4299	dated sample not necessarily associated with hominid remains Mousterian	*R* **14** (1972): 59 *CFH* **2** (1971): 338–340 Smith (1976*b*) Wolpoff (1979): 67–114
Sacco-pastore, Italy	41°57′N 12°32′E	1929	2 adult crania, one fragmentary (Levels 5 and 7; Saccopastore 1 and 2)	58 000 ± 500 (A3)	wood	GrN–2572	date (obtained after isotopic enrichment) for sample from remote correlated deposit; date of *c.* 60 000 bp inferred for hominid remains Mousterian	*R* **9** (1967): 103 *CFH* **2** (1971): 254
Saint-Brais, Berne, Switzerland	47°19′N 7°09′E	1955	adult incisor (depth 2·9 m; Saint-Brais 1)	33 400 ± 1700 (A3)	bone of *Ursus* from 2·4 m depth	B–838	date of *c.* 40 000 bp inferred for Saint-Brais 1 presumed final Mousterian	*CFH* **2** (1971): 306 (not publ. in *Radiocarbon*)
Arcy-sur-Cure (Grotte du Renne), Yonne, France	47°36′N 3°46′E	1950–58	teeth (Bed 8; Arcy 14–22)	33 860 ± 250 (A2)	charred bone	GrN–1742	Châtelperronian with Mousterian element	*R* **5** (1963): 166 *CFH* **2** (1971): 77
Combe-Grenal, Dordogne, France	44°48′N 1°12′E	1953	juvenile mandible, fragmentary adult cranium and mandible, teeth, fragmentary skeleton (Bed 25; Combe-Grenal 1 and 2)	39 000 ± 1500 (A2)	charred bone and ash from Layer E2	GrN–4304	Mousterian of La Quina type	*R* **9** (1967): 112 *CFH* **2** (1971): 102

Regourdou, Dordogne, France	45°03′N 1°11′E	1957	adult mandible and partial skeleton (Bed 4; Regourdou 1)	45 500 ± 1800 (A2)	wood from Bed 4	GrN–4308	Mousterian	*R* **9** (1967) : 112 *CFH* **2** (1971) : 164
La Quina, Charente, France	45°30′N 0°19′E	1908–15, 1920, 1965	fragmentary remains of at least 20 individuals (Bed 1–4; Quina H1–H27)	35 250 ± 530 (A3)	charred bone from Bed 1	GrN–2526	dates latest Mousterian occupation level	*R* **5** (1963) : 165 *CFH* **2** (1971) : 162
Bañolas, Spain	42°07′N 2°45′E	1887	adult mandible (Bañolas 1)	17 600 ± 1000 (A2)	travertine matrix	UCLA–93	date is very late for Neanderthal remains, but the accuracy of a radio-carbon age based on travertine is uncertain as there is the possibility of subsequent exchange with more recent carbon; no archaeological associations.	*R* **8** (1966) : 480 *CFH* **2** (1971) : 288
La Cotte de St Brelade, Jersey, C. I.	49°12′N 2°12′W	1910–11	adult teeth (St Brelade 1)	47 000 ± 1500 (A3)	charcoal (black ashes)	GrN–2649	Mousterian	*R* **5** (1963) : 1965 *CFH* **2** (1971) : 37
Forbes' Quarry & Devil's Tower Gibraltar	36°08′N 5°18′W	1848, 1926	adult cranium (Gibraltar 1); fragmentary cranium and mandible of child (Gibraltar 2)	47 700 ± 1500 49 200 ± 3200 >47 000 (A3)	charcoal from Layer G (uppermost Mousterian layer) in Gorham's Cave, Gibraltar	GrN–1473 GrN–1556 GrN–1678	dating based on correlation with Gorham's Cave Mousterian (Gibraltar 2)	*R* **6** (1964) : 350 *CFH* **2** (1971) : 218, 219
Jebel Irhoud, Morocco	31°56′N 8°52′W	1961	adult cranium and calvaria, mandible of child (Irhoud 1, 2, and 3)	>32 000 (A2)	animal bone from same layer	Ny–73	Levalloiso-Mousterian	*R* **10** (1968) : 123 *CFH* **1** (1977, 2nd ed.) : 81

age measurement, liquid scintillation counting. In practice, the far limit of methods of dating based on measurement of radioactive decay is normally some ten half-lives, when only about one-thousandth of the initial activity is left. The half-life of ^{14}C is 5730 ± 40 years (although the original, 3% lower, Libby value of 5570 ± 30 years is used for calculating conventional radiocarbon ages; Godwin 1962), and the specific activity of ^{14}C in nature is about 14 disintegrations per minute per gram of carbon so that the initial level is low. The practical limit of radiocarbon age measurement by conventional counting methods is about 50 000 years although by isotopic enrichment the range can be extended by a further 20 000 years (Erlenkeuser 1979, Grootes 1977, Grootes & Stuiver 1979, Grootes *et al.* 1980, Haring *et al.* 1958). In addition, natural variations in the concentration of ^{14}C over past millennia have resulted in discrepancies between the radiocarbon time scale and solar years and no very exact allowance can yet be made for this beyond the far limit of the bristlecone pine calibration at about 8000 calendar years before present (BP) (Olsson 1970).

Measurement of the amount of ^{14}C in any given sample by detecting the relatively infrequent decay of ^{14}C atoms is an inefficient procedure in comparison with the theoretical ideal of determining the total number of ^{14}C atoms present by direct measurement of some physical constant such as their mass (Stuiver 1978*a*). It is essentially by this means, using a mass spectrometer to detect specific ions, that the concentration of stable (that is, non-radioactive) ^{13}C in ^{12}C, the common stable isotope of carbon, is measured. The natural abundance of ^{13}C is, however, about 1·1%, whereas that of ^{14}C in ^{12}C in modern living material is about 1 part in 10^{12}, some ten orders of magnitude less than the relative abundance of ^{13}C. Hitherto, no mass spectrometric methods were available with the sensitivity necessary to allow the direct detection of such small amounts of any element, still less the residual amounts of ^{14}C in ancient organic material in which appreciable radioactive decay has occurred (for example 1 part in 10^{13}, 1 in 10^{14} and 1 in 10^{15} of ^{14}C in ^{12}C in 20 000, 40 000 and 60 000 year-old material, respectively). Now the long-sought ideal of direct measurement of ^{14}C, previously regarded as unattainable, is near to realization.

In recent years there has been increasing interest among nuclear physicists in the development of methods for the detection of long-lived radioisotopes having a very low natural abundance, and half-lives of the order of several hundred-thousand to several million years (Allen 1980). Some of these nuclides (for example the cosmogenic radionuclides ^{10}Be, ^{26}Al and ^{36}Cl) may eventually become the basis of geological dating methods if their geochemistry proves favourable, while others (for example ^{129}I) have a particular bearing on such questions as the age of the solar system and the ages of meteorites. The search for these rare or very rare elements as well as other, more fundamental, research in nuclear physics, has provided much of the impetus for the design of particle accelerators and cyclotrons for use as high energy mass spectrometers. A logical development from this is the application of the same methods to the detection and measurement of the relatively much shorter lived and much more abundant cosmogenic radionuclide ^{14}C (Bennett *et al.* 1977, 1978, Gove 1978, Muller 1977, 1979, Muller *et al.* 1978, Nelson *et al.* 1977, Stephenson *et al.* 1979). The methodology of high energy mass spectrometry is well described in the references cited here and at the end of the next paragraph. Here it is sufficient to note the higher energy (some 10^3 times that typical for conventional mass spectrometers) needed to obtain good resolution of the closely similar masses of the three isotopes of carbon, ^{12}C, ^{13}C and ^{14}C, and the need (much more difficult to satisfy) for virtually 100% discrimination against unwanted ions of the same mass (for example, ^{14}N).

Accelerators or cyclotrons built primarily for nuclear physics research are not necessarily either ideal or routinely available for radiocarbon dating, so that 'dedicated' machines are needed for the purpose. Of the possible alternatives, accelerators based on the tandem Van de Graaff principle have been preferred for the high energy mass spectrometers now under construction for radiocarbon dating, for example the dedicated machine being built at Oxford with the support of the Science Research Council (Doucas *et al.* 1978, Hall 1980, Hedges 1981).

The high capital cost of accelerator-based laboratories probably implies that relatively few will ever be built even on a world-wide basis and that they will not supersede conventional radiocarbon dating laboratories for most purposes, but for some applications high energy mass spectrometric methods will have unassailable advantages over existing methods of radiocarbon dating and these can be summarized very quickly. Firstly, the efficiency of detection of ^{14}C by accelerator methods is several orders of magnitude higher than that of methods based on radioactive counting. Thus samples of only a few milligrams or less of carbon will be needed, compared with the amounts of several grams needed for most conventional radiocarbon age measurements. Secondly, the increased sensitivity of accelerator methods will allow age measurements to be made to within the same statistical accuracy as that attainable by conventional methods, but in a much shorter time (minutes or hours rather than days). Thirdly, the age range will be greater than that of conventional methods and may ultimately be extended to 100 000 years bp with the aid of laser enrichment (Hedges & Moore 1978). Small gas counters of a few millilitres in volume, with very low background counting rates and excellent long-term stability, have recently been successfully developed (from solar neutrino research) for the measurement of samples of a few milligrams of carbon (Harbottle *et al.* 1979), but long counting times are needed (typically 70 days) and the far limit of age attainable without enrichment is likely to be about 20 000 years for 10 mg samples. Although for some applications the role of small counters will be complementary to that of accelerators, their performance will not rival that of accelerators for very old samples.

Contamination, particularly by younger organic substances, is a limiting factor in the accuracy of radiocarbon dating and becomes increasingly important as the true age of samples increases. This applies equally to all radiocarbon age measurements whether made conventionally or by high energy mass spectrometry. Time-consuming chemical pretreatment is necessary to remove potential contaminants from almost all of the organic materials commonly used as samples for radiocarbon dating. This preliminary chemistry requires roughly the same expenditure of time and effort whatever final method of measurement is used. On the other hand, the very small amounts of sample required for radiocarbon age measurement by high energy mass spectrometry will allow refined chemistry and chemical methods to be used for the separation of ultra-pure specific substances (for example, hydroxyproline, the amino-acid exclusive to bone collagen; Hedges 1981) for reduction to elemental carbon (graphite) for introduction to the ion source of the accelerator. Less than 1 g (possibly as little as 0·2 g) of compact bone, or about one five-hundredth of the amount normally required for dating, will probably be needed to provide an adequate sample of hydroxyproline.

The implications of all this for the more exact dating of the fossil remains of Neanderthal man are clear, although it may be some time before the full potential of the accelerator method can be realized and the desired accuracy of measurement of better than ±0·5% attained in practice for samples 50 000–75 000 radiocarbon years old. Some of the most important remains of Neanderthal man from the evolutionary point of view are from historic excavations of sites that were dug under what would be regarded today as non-ideal conditions with inadequate stratigraphical and other controls. Direct sampling of these remains should enable these important fossils to be accurately dated and placed in their correct chronological sequence, allowing present doubts and arguments about stratigraphical correlations to be finally resolved. For more recently excavated remains where the stratigraphy is not in doubt and for further discoveries that may be made in the future, the value of direct dating of skeletal remains, without the need to sacrifice appreciable quantities of palaeontologically important material, will be very great.

The survival of sufficient collagen for dating (and by inference, of hydroxyproline) in very ancient bone has yet to be demonstrated, but it is likely that it will be possible to date human bone directly by this means at least within the normal range of the conventional methods of radiocarbon age measurement. Production of ^{14}C *in situ* through capture by ^{14}N of thermal neutrons arising from cosmic radiation does not ordinarily have a significant effect on radiocarbon samples at or near sea level (Harkness & Burleigh 1974), but might have to be taken

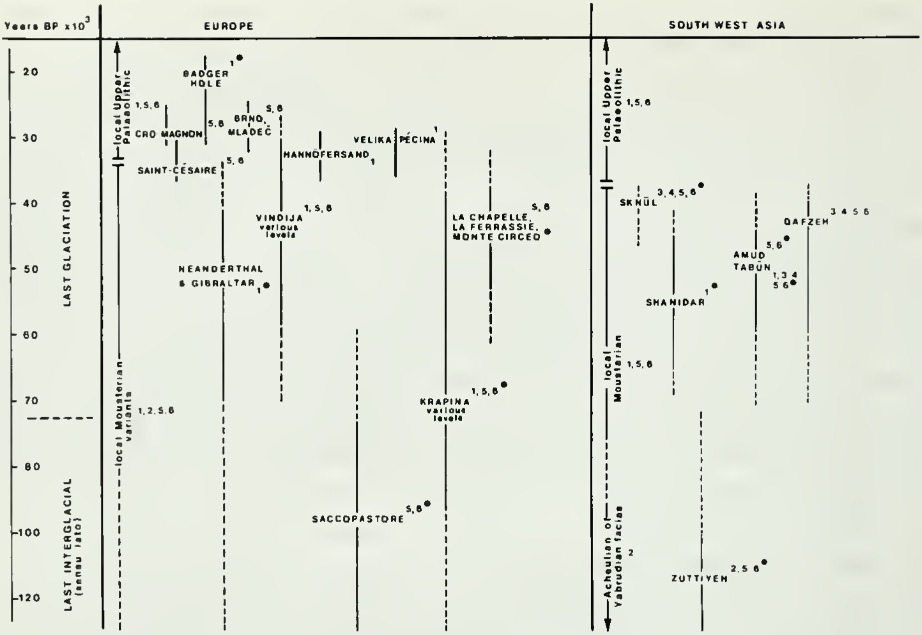

Fig. 2 Ranges of uncertainty in dating Neanderthal and other fossil hominid material of the Upper Pleistocene. The vertical arrangement of sites has no evolutionary significance. 1 = indirect ^{14}C date; 2 = uranium series date; 3 = direct amino-acid racemization date; 4 = amino-acid racemization date (faunal); 5 = sedimentological or stratigraphic correlation; 6 = faunal correlation. References used in the compilation of this table and not quoted elsewhere are Bräuer (1980), A. J. Jelinek (in press), J. Jelínek (1976), Smith (1976*a*).

into account in nitrogenous material (such as collagen) more than 50 000 years old. Another possible uncertainty relates to the occurrence of natural ^{14}C variations in the remote past for which only indirect evidence, suggesting that these were not inordinately large, is available at present (Barbetti 1980, Stuiver 1978*b*). In the longer term, measurement by the accelerator method of ^{14}C in carbon dioxide occluded within the annual layers of polar ice cores, or in carbonates (foraminifera) from ocean sediments correlated by magnetostratigraphy, together with conventional $^{13}C/^{12}C$ (and $^{16}O/^{18}O$) measurements, may allow the extent of natural ^{14}C variations during the upper Pleistocene to be more fully determined.

Concluding remarks

The above review of our present state of knowledge concerning the dating of Neanderthal and related hominids has shown the severe limitations of present methods of relative and absolute dating in resolving the crucial evolutionary problems of this period of the Upper Pleistocene. The present powers of resolution of the various methods available, and the associated chronological ranges of uncertainty for specific hominid sites are summarized in Fig. 2. It is evident that the application of radiocarbon dating using particle accelerators has the potential to resolve many of the areas of uncertainty embodied in Fig. 2 and much of the fossil material listed is already available for measurement, as indicated by an asterisk. The direct dating of such hominid finds from the Upper Pleistocene should be a primary task of this new method as soon as it comes into operation. This will be of inestimable value to our understanding of the more recent stages of human evolution.

Acknowledgements

We should like to thank Dr K. P. Oakley, whose continuing interest in the dating of early man has been a constant source of stimulus, Dr R. E. M. Hedges, Research Laboratory for Archaeology, University of Oxford, Professor E. M. Jope, Archaeology Department, The Queen's University of Belfast, Dr J. Clutton-Brock, Department of Zoology, British Museum (Natural History), and Dr M. S. Tite, Keeper of Research Laboratory, The British Museum, for discussion and comment. We also wish to thank the photographic studio of the British Museum (Natural History) for Fig. 1.

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